A BASIS FOR ASEISMIC DESIGN OF STRUCTURES

BY

EMILIO ROSENBLUETH

C.E., Universidad Nacional de Mexico, 1948
M.S., University of Illinois, 1949

AN ABSTRACT OF A THESIS

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The present investigation endeavors to develop a procedure for analyzing elastic structures subjected to seismic motions.

There is little hope at present for predicting the intensity and characteristics of future earthquakes. Still, it is possible to establish a rational basis of design. Although the manner in which one should vary the factor of safety according to location and type of structure must be left to engineering judgment, it is clear that, under a given set of conditions, a single uniform factor of safety will produce the most adequate design. The kernel of the proposed basis for design consists in striving for a uniform factor of safety, from which one can always depart in accordance with judgment. The method gives deflections and stresses, design for which will result in structures having a uniform factor of safety.

Two basic assumptions are made in the analysis:

1. The structure behaves elastically.

2. There is no ground coupling; i.e., the feedback of energy from the structure to the ground is neglected.

Although the methods derived in this investigation can be extended to include effects due to damping and ground coupling, only those ideal structures which comply with the above assumptions are analyzed in detail.

There are no means for assuring that the few reliable records of destructive earthquakes which are now available constitute a representative sample of destructive earthquakes in general. Hence, some theoretical considerations concerning the characteristics common to destructive earthquakes are necessary in order to establish a reliable basis for design. These considerations lead to conclusions that depend on the type of ground upon which the structure in question is founded.

In every case the motion is known to originate through a markedly irregular process. Moreover, ordinarily the shock waves that reach a structure must first travel through geological formations that are also of a highly irregular character. Structures founded on firm ground are, therefore, acted upon by ground motions consisting of nearly random arrays of waves. This is not exactly the case for structures founded on thick, soft strata, for under these circumstances all waves undergo, at a certain stage, nearly the same processes of reflection, refraction, and dispersion. Accordingly the present study is divided into two parts. The first concerns structures resting on firm ground; the second deals with structures founded on a layer of soft soil.

The first part of the investigation leads to the following conclusions.

1. Destructive earthquakes can be idealized as nearly random sequences of concentrated acceleration pulses (sudden changes of ground velocity). Comparison of the effects of these motions with those of true earthquakes on simple structures indicates that the idealization is satisfactory down to natural periods of about 0.15 or 0.20 sec; shorter natural periods have relatively little structural importance. This is in agreement with conclusions due to G. W. Housner.

2. Responses of elastic structures having more than one degree of freedom can be computed, once the ground motion is known, by means of a relation similar to Duhamel's integral for simple structures. The equation states that a response is given by the integral, with respect to time, of the ground acceleration multiplied by a certain function f depending solely on structural properties and on whether the type of response in question is shear stress, deformation, direct stress, etc.

3. When the period of f is short in comparison with the earthquake duration, design responses are proportional to the square root of the average of f^2. The average is taken over a time interval equal to the period of f. Under these conditions a design response is equal to the square root of the sum of the

squares of responses associated with the natural modes of the structure being investigated.

4. When the function f is aperiodic, or its period is not short compared with the earthquake duration, the foregoing relationship errs on the unsafe side. An answer can be got by bracketing the design response. For this purpose one may idealize the earthquake as having constant intensity and lasting for only a short time, say ten seconds. The idealization gives an upper limit to the design response, obtained by substituting the maximum 10-sec average of f^2 for the average used in paragraph 3. The two limits are usually sufficiently close for practical purposes. When this is not the case a satisfactory solution cannot be obtained without considering energy losses and the variation of earthquake intensity with time, for which there exist at present no quantitative data.

5. Actual earthquakes differ from the fictitious motions investigated in that ground accelerations are in reality finite. Accordingly the duration of seismic waves is not infinitely short, as is that of concentrated pulses. A correction for this factor modifies design responses only to a small degree, so that a radical simplification of seismic waves is permissible. For simplicity seismic waves are here idealized as half sine waves. The effect of replacing concentrated pulses by waves of finite duration amounts to replacing f by a slightly different function. Once the substitution is made, conclusions 3 and 4 apply without modification. The substitution extends the applicability of conclusions derived from the fictitious motions to a wide range of natural periods.

6. Application of this method of analysis to tall buildings idealized as uniform shearbeams (slopes proportional to shears) discloses that design shears vary approximately as a parabola with vertex at the top of the building. The shear distribution differs appreciably from a parabola only at the topmost two stories. This distribution is in marked contrast with the straight line that is obtained from the conventional static method of design.

7. A more basic error associated with the static method of design is its dimensional inconsistency. According to the static method, stresses and deformations increase in direct proportion to the mass. The present investigation, in accordance with previous studies by H. M. Westergaard, M. A. Biot, and G. W. Housner, leads to the conclusion that stresses vary approximately in proportion to the square root of the product of mass and stiffness, and that deformations vary approximately in proportion to the square root of the quotient mass/stiffness. This conclusion applies to all elastic structures and is not contingent upon a number of the idealizations made in the present study. Deviations from ideal elastic behavior accentuate the inconsistency of the static method.

Most of the foregoing conclusions have been derived analytically and confirmed by empirical studies of fictitious motions consisting of random sequences of concentrated pulses.

The proposed method of analysis is illustrated further by application to a two-story bent and to tall buildings idealized as shearbeams with offsets.

In the second part of the investigation, concerning structures founded on soft ground, the structure is assumed to rest on a layer bounded by horizontal planes that extend to infinity in all directions. It is assumed, moreover, that the layer rests on a semi-infinite bedrock formation and that both deposits are homogeneous. Surface waves are neglected.

Both the soft layer and the bedrock are first idealized as elastic materials. The study is next extended to include viscoelastic behavior of the soft layer as well as of the bedrock. The latter assumption seems justified by available test data on silty and clayey soils.

A numerical method is developed for computing design responses of structures that rest on a soft layer. The method has no limitations other than the assumptions mentioned above. It is applicable to elastic as well as viscoelastic layers,

to structures with any number of degrees of freedom, and to earthquakes with constant or variable intensity. Computations can be carried to any degree of accuracy. The method can be extended to cover the case of structures founded on a series of soft layers.

This numerical procedure involves lengthy computations. For this reason a simple, approximate procedure is also developed. There is no difficulty in estimating closely the maximum possible error involved in the approximate method. The error is usually negligible but may attain significant magnitudes under exceptional geological conditions. In the latter case resort must be made to the lengthier numerical method.

The following conclusions are derived from the second part of the investigation.

1. The factor by which design responses that correspond to structures on firm ground must be multiplied to obtain those corresponding to structures on soft ground tends to unity as the fundamental period of the structure increases.

2. For simple structures this factor reaches maximum but finite values whenever the natural period of the structure coincides with the fundamental period of the soft layer or with an odd submultiple thereof.

3. In the case of elastic media these maxima are all equal. Minima occur in the neighborhood of natural periods that coincide with even submultiples of the fundamental ground-period. The minima are approximately equal to unity.

4. In the case of viscoelastic media, design responses are always smaller than those for the corresponding elastic conditions. This difference increases, except for local variations, with decreasing structural periods.

Methods of analysis developed in this part of the investigation are illustrated by numerical examples.

The assumptions of elastic behavior and absence of ground coupling limit the range of conditions to which these con-

clusions may be applied with satisfactory accuracy. Moreover, the simplifications introduced in the case of structures founded on soft ground, although reasonable, invite errors of unknown magnitude.

VITA

Emilio Rosenblueth was born on April 8, 1926, in Mexico, D.F., Mexico. After being graduated from the Colegio Morelos Preparatory School in 1942, he entered the Universidad Nacional de Mexico and received the degree of Civil Engineer from that institution in June, 1948. From 1945 to 1948 he worked part time as surveyor and as construction supervisor in various projects. In 1948 he was laboratory assistant for the Ministry of Hydraulic Resources in Mexico, and later was engaged in the design of several reinforced concrete structures. He entered the Graduate College of the University of Illinois in September, 1948, and received the degree of Master of Science in Civil Engineering in August, 1949. He held a Fellowship from the Fundación Manuel Suárez during his first two semesters at this university, a Tuition Scholarship during his first semester, a Research Assistantship in the Department of Civil Engineering from February, 1949 to June, 1950, and a Fellowship in the same Department during the academic year, 1950-1951. He is coauthor, with Mr. Rockwell Smith and Mr. H. O. Ireland, of the Fifth Progress Report of Joint Investigation of the Stability of Roadbeds and Embankments, published in Bulletin 486 of the American Railway Engineering Association. He is a Junior Member of the American Society of Civil Engineers, Member of the Seismological Society of America, Student Member of the American Concrete Institute, and Associate Member of Sigma Xi.